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# Physicochemical and Mineralogical Characterization of Ciuyah Mud Volcano: Rare Earth Elements and Salt Minerals for the Advanced Materials Industry, Indonesia

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## ABSTRACT

The Ciuyah Mud Volcano in West Java is a notable geological feature resulting from mud extrusion driven by subsurface pressure, buoyancy, and thermal variations. Its unique characteristics provide valuable insights into Earth's subsurface processes. Materials ejected from mud volcanoes often contain valuable minerals that are crucial for scientific investigation and economic application. Of particular interest at this site is the presence of Rare Earth Elements (REEs), which are vital for modern technology. The aim of this study is to provide a comprehensive characterisation of the Ciuyah Mud Volcano. The objectives are to: (1) determine its physicochemical properties using electrical conductivity (EC), volumetric water content (VWC), and total dissolved solids (TDS) measurements; (2) identify the distribution of REEs using X-Ray Fluorescence (XRF) and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES); and (3) analyze the salt mineralogy using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). The results revealed high conductivity in the mud, as evidenced by elevated EC and VWC values, as well as high TDS and salinity in the water samples. XRF and ICP-OES analyses confirmed the presence of twelve REEs: Ce, Dy, Eu, Gd, Ho, La, Nd, Pr, Sm, Tb, Sc, and Y. Furthermore, SEM and XRD identified Halite and Helvite as the primary salt minerals, characterized by large, hexagonal crystal structures. These findings highlight the potential of the Ciuyah Mud Volcano as a source of strategic REEs for Indonesia's advanced

materials and clean energy sectors, while also offering local socioeconomic applications, such as salt-based cosmetic products.

**Keywords:** Ciuyah Mud Volcano, rare earth elements, geochemical, resource potential, SEM, XRD

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## INTRODUCTION

A mud volcano is a geological phenomenon characterized by the extrusion of mud from beneath the Earth's surface driven by subsurface pressure, buoyancy, and temperature [1]. In Indonesia, mud volcanoes are distributed across several regions, including West Java, Central Java, and East Java, following the sedimentary basins of the Java-Madura Depression within the Bogor–Serayu Utara–Kendeng–Madura Strait Zone [2]. The distribution of these mud volcanoes follows the pattern of sedimentary rock deposition and geological faults on the Java islands [3]. One notable example of a mud volcano in West Java is the Ciuyah Mud Volcano in Ciniru Village, Kuningan Regency.

The Ciuyah Mud Volcano is renowned for its constant eruptions of salty water and mud. The local community therefore, refers to the area as 'Ciuyah', which means 'salt water' in Sundanese. Although the eruptions are relatively small, they are persistent, and it is believed that the discharged materials contain valuable minerals transported from deep within the Earth. According to residents, the mud volcano has existed for decades, but no one knows how or when it first appeared [4]. The Ciuyah system exhibits conduit pathways that channel mud, gas, fluids, chemical elements, and minerals from depth to the surface [5, 6]. Some of the unique minerals found in the mud are of particular importance to modern technology. Some of these minerals are rare earth elements (REEs), which are available for exploration [7]. This makes Ciuyah especially interesting due to its potential to host both strategic minerals and natural salt deposits [8].

Rare earth elements (REEs) are a group of 17 elements, from lanthanum (La) to lutetium (Lu), that play a key role in modern technology. They are widely used in electronic devices, including smartphones, rechargeable batteries, permanent magnets, LED lights, and green energy technologies such as wind turbines and electric vehicles [3, 9]. Although Indonesia possesses substantial REE reserves estimated at approximately 1.5 billion tons, most remain unexplored [10]. A geochemical study at the Bledug Kuwu mud volcano in Central Java successfully identified REEs such as Ce, Dy, Eu, Gd, Ho, La, Nd, Pr, Sm, Tb, Y, and Sc, with Ce and La as the dominant elements, highlighting the considerable potential of mud volcanoes as REE sources [7]. However, the Ciuyah Mud Volcano has never been comprehensively studied, leaving its geochemical and mineralogical characteristics as a significant research gap, while also supporting the development of Indonesia's advanced materials industry.

In addition to its REE potential, Ciuyah Mud Volcano is unique for its consistent discharge of saline water, suggesting the presence of natural salt accumulation that could be utilized. Salt is widely used not only for household consumption but also in various industries, including health, cosmetics, and agriculture. It plays an important role in digestion, detoxification, and skincare [11]. In 2022, Indonesia's national salt demand reached 4.5 million tons, while

domestic supply from key production centers such as Cirebon, Madura, Pati, and Sumenep remained insufficient [12, 13]. Thus, identifying new potential sources of salt such as from the Ciuyah area is both relevant and necessary for exploration.

Based on these considerations, this study aims to provide the first detailed physicochemical and mineralogical analysis of the Ciuyah Mud Volcano, focusing on the variation in REE content and unique salt minerals. Ex-situ measurements were performed on collected samples. The mud's physical properties were tested for electrical conductivity (EC) and volumetric water content (VWC) using a Decagon EM-50. The physical properties of the water sample were tested for EC, total dissolved solids (TDS), pH, and temperature using a Hanna Combometer. Ex-situ measurements were conducted on mud samples to determine Electrical Conductivity (EC) and Volumetric Water Content (VWC) using a Decagon EM-50, while water parameters, including EC, Total Dissolved Solids (TDS), pH, and temperature, were measured using a Hanna Combometer. Laboratory analyses to determine metal and mineral contents were performed using X-Ray Fluorescence (XRF), which rapidly detects elements, and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), which provides high sensitivity for quantifying metals in mud samples [14]. Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) methods were employed to identify the morphological form of particles and the crystal structure of formed minerals or salts. SEM was used to observe the microscopic structure of particles visually, while XRD was used to determine crystalline phases and mineral composition [15].

These findings are expected to expand scientific understanding of mud volcano phenomena while opening opportunities for the utilization of new natural resources for strategic industries and national resource security, particularly in supporting the advancement of materials science, energy innovation, and green technology industries in Indonesia. This study aims to identify the presence and variation of rare earth elements (REEs) and natural salts in the Ciuyah mud volcano by taking a physical-chemical and mineralogical analytical approach. These findings will contribute to the scientific understanding of mud volcano phenomena, opening up opportunities to utilize new natural resources in order to support strategic industrial needs and national resource resilience. Ultimately, this research will advance Indonesia's materials science, energy innovation and green technology industries.

## METHODOLOGY

This research was conducted at the Ciuyah Mud Volcano in Ciniru Village, Kuningan Regency (see FIGURE 1). The samples used were mud, water, and salt. The equipment used included a paralon pipe, a Decagon EM-50 measuring instrument with sensors, sample bottles, a Hanna Combometer, and a TP101 digital thermometer (see FIGURE 2). Sampling of mud and water was carried out at 10 points distributed across the research site and accessible surrounding areas. These points represented the center of mudflow activity, water mixed with mud deposits in flooded zones, and the transition areas toward the surrounding land, ensuring that the collected data were representative of the entire study area.

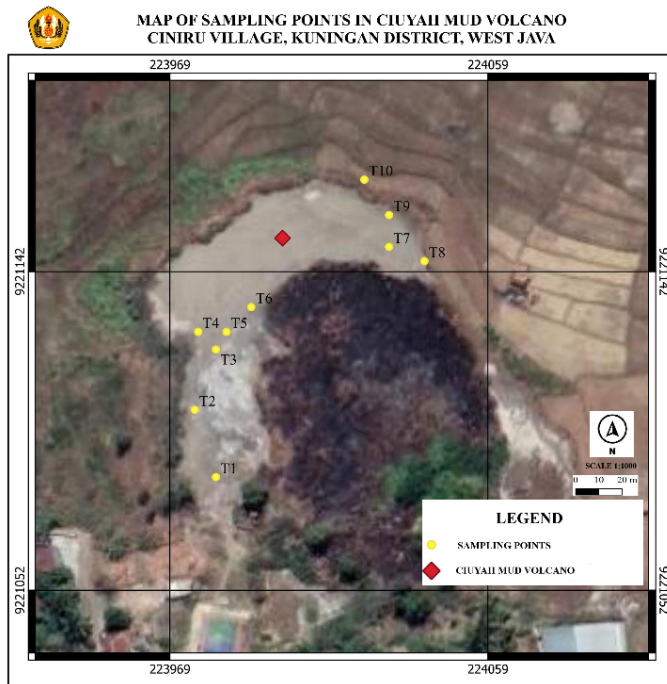
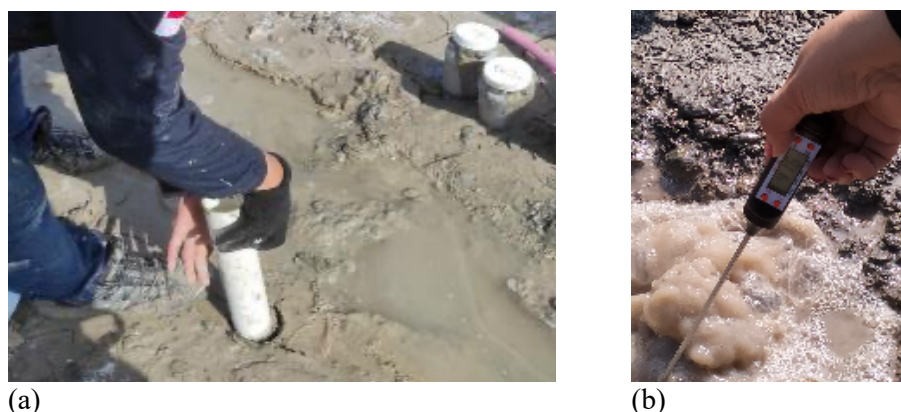


FIGURE 1. Map of sampling points in Ciuyah Mud Volcano.



FIGURE 2. Tools and material used for data measurement.

Mud samples were collected using two techniques: (1) the coring technique, to preserve the integrity of the samples and represent the original stratigraphic conditions, so that the vertical distribution of physical parameters, such as EC and VWC, can be analyzed accurately, and (2) direct collection into sampling bottles (FIGURE 3a). Water samples were collected using sampling bottles at accessible manifestation points. The TP101 digital thermometer was immersed directly into the water on site to measure temperature (FIGURE 3b). Salt samples were collected by placing them into sampling bottles.



**FIGURE 3.** (a) In-situ mud sampling; (b) In-situ temperature measurement.

The electrical conductivity (EC) and volumetric water content (VWC) were then measured using a Decagon EM-50 with a 5-TE and EC-5 sensor, and the results were displayed in the ECH20 Utility software. Measurements were taken by inserting the sensors horizontally in parallel positions, with measurements taken at 5 cm intervals every 5 minutes at each depth to ensure data stability. The 5 cm interval was determined according to the size of the sensors (FIGURE 4a). The EC, TDS, and pH parameters in the water samples were measured using a Hanna Combometer (FIGURE 4b). To improve data accuracy, measurements were repeated three times, and the average value at each point was recorded, providing more reliable results while minimizing errors.



**FIGURE 4.** (a) Mud samples measured ex-situ with Decagon EM-50; (b) Water samples measured ex-situ with Hanna Combometer.

The mud samples in bottles were then subjected to XRF and ICP-OES tests at the Instrumentation, Electrical and Laser – Metallurgical Laboratory, BRIN, Serpong, to obtain the content of various elements and the rare earth elements (REEs). Additionally, salt samples in bottles were analyzed using SEM and XRD at the Hydrogeology Laboratory, Institut Teknologi Bandung, to identify morphology and mineral composition.

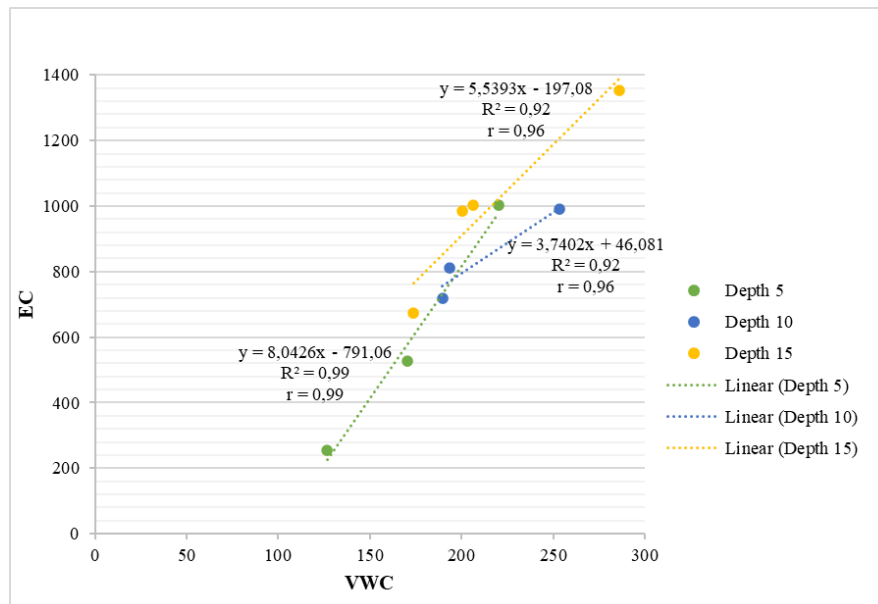
## RESULT AND DISCUSSION

### Measurement of the Physical-Chemical Properties of the Ciuyah Mud Volcano

Based on the Decagon EM-50 measurement data, a range of EC and VWC values is shown for all samples, ranging from 253.9–1354 mS/cm and 126.6–286 m<sup>3</sup>/m<sup>3</sup>, respectively. The depth is measured by sensor readings between 5 and 15 cm, as shown in TABLE 1. TABLE 1 shows that point C8 has a high conductivity value. This is because it is a transition area from wet mud to dry. The high EC value is likely due to dissolved minerals that make the area more conductive. This is thought to be due to the presence of metal elements, such as heavy metals, REEs, or salt, which collectively increase conductivity [16, 17].

**TABLE 1.** Results of measurements of Ciuyah Mud Volcano samples

Sample Point	Depth (cm)	EC (mS/cm)	VWC (m <sup>3</sup> /m <sup>3</sup> )
C1	10	811	193.7
C2	15	672.9	173.8
C3	5	1002.5	220.1
C4	15	983.6	200.6
C5	10	990.8	253.3
C6	5	526.8	170.2
C7	5	253.9	126.6
C8	15	1354	286
C9	10	717.6	189.7
C10	15	1002.6	206.4



**FIGURE 5.** Scatter plot diagram showing the relationship between EC and VWC in samples of Ciuyah Mud Volcano.

According to [15, 18, 19], a positive coefficient of determination ( $R^2$ ) value between 0.76 and 1 indicates a very strong relationship. FIGURE 5 shows that the correlation coefficient ( $r$ ) is positive, and the coefficient of determination ( $R$ ) is also positive, approaching one at each depth, indicating a significant influence of VWC on EC. This condition indicates that water content plays an important role in increasing electrical conductivity through ion transport [16, 20]. Thus, zones with high EC and VWC are also potential pathways for REE migration and accumulation. Sample C8 exhibits the highest EC and VWC values and is presumed to contain numerous conductive minerals.

Furthermore, the EC and TDS values of the water samples from the Ciuyah Mud Volcano are high. This indicates a high concentration of dissolved solids, suggesting a high mineral content at the sampling point. It is thought that the Ciuyah Mud Volcano water sample is saline and has a high salinity level. The conductivity value for saline water is 1,000–10,000  $\mu\text{S}/\text{cm}$  [18]; this high salinity is believed to be due to the tectonic compression process occurring beneath the Northern Javanese Sea. A high TDS value in seawater indicates the presence of many chemical compounds [21]. Furthermore, the TDS value in seawater has a high salinity level, indicating that the water contains many chemical compounds [18]. As shown in TABLE 2, the average temperature of the water at the Ciuyah Mud Volcano is 36°C. This falls within the hot spring and low-temperature geothermal system categories.

**TABLE 2.** Results of measurements of Ciuyah Mud Volcano samples

Sample Point	Temperature (°C)
Point 1	41.4
Point 2	32.5
Point 3	30.5
Point 4	32.2
Point 5	36.6
Point 6	33.9
Point 7	38.4
Point 8	43.2
Point 9	36.9
Point 10	41.6
Point 11	37.1
Point 12	34.4
Point 13	36.2
Point 14	33.5
Point 15	31
<b>Average Temperature (°C)</b>	<b>36</b>

The saltwater at the research site is brownish in colour, has a slight scent, and tastes salty. This is due to the presence of clay on the surface of the research area. The salty taste of the mud is

due to its proximity to the sea and the presence of chloride (Cl) elements. These elements cause a reaction between sodium (Na) and Cl ions, resulting in the salty taste. The scent is caused by sulphate content, which supports the idea that the saltwater manifestation is due to active tectonic activity involving hot water ranging in temperature from 20°C to 100°C [21]. The pH value of the Ciuyah Mud Volcano ranges from acidic to neutral (FIGURE 6), suggesting that its hydrogeochemical conditions are influenced by subsurface fluid interactions [22].

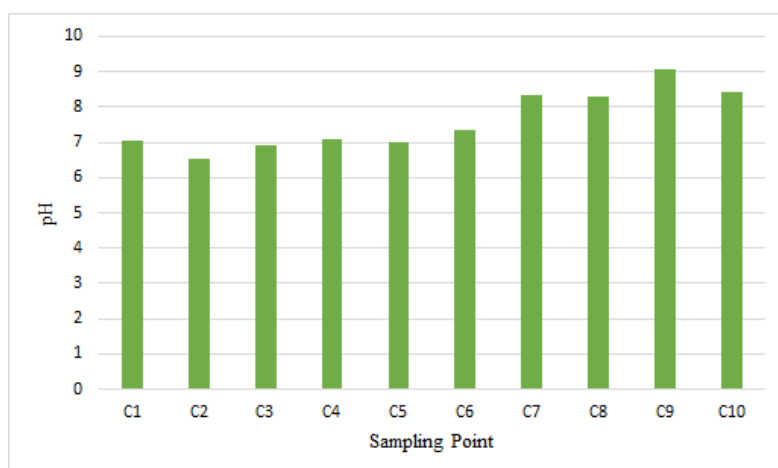


FIGURE 6. Bar diagram of the results of pH using the Hanna Combometer.

### Analysis of Rare Earth Elements (REEs) using XRF and ICP-OES of the Ciuyah Mud Volcano

The REE content of samples from the Ciuyah Mud Volcano can be determined using XRF and ICP-OES testing. XRF testing is used to analyze variations in the elements present in the mud samples. This test detects 23 elements: Si, Fe, Ca, Al, Cl, K, Sr, Ti, Mn, Px, As, Nb, Zn, Mo, Rb, In, Sn, Ru, Sb, Rh, Te, U and Sc. These elements are then categorised as major (levels >1%), minor (levels 0.1–1%) or trace (levels <0.1%) elements [23]. The elements with levels above 1% are Si, Ca, Fe, Sr, Cl, Al, K and Sc, with Si having the highest content value (35.75%). Mn, P, As and U are categorised as minor elements, while the remaining elements are categorised as trace elements. Apart from that, there are trace amounts of heavy metals including Zn, Mn, Al, and As. It is suspected that the Ciuyah Mud Volcano area is still in its natural state and has not been exposed to industrial wastewater containing heavy metals. The elements Fe and Ti are among the main natural magnetic minerals found in rocks and sediments [24]. Iron (Fe) is believed to be present in oxide compounds, as rare earth metals can be identified by oxide compounds that match the characteristics of rare earth metals found in oxide materials [7]. Therefore, the XRF analysis results also indicate the presence of rare earth elements, including scandium (Sc).

Further analysis of the suspected REE discovery was carried out using ICP-OES. This analysis revealed the presence of 12 rare earth metal elements: Ce, Dy, Eu, Gd, Ho, La, Nd, Pr, Sm, Tb, Sc, and Y (see FIGURE 7). The light REEs contained in the Ciuyah Mud Volcano are Ce, La, Nd, Pr, and Sm. Meanwhile, the elements Dy, Eu, Gd, Ho, Tb and Y are classified as heavy

REEs [7]. Element Y is only detected in sample C5 because its concentration is the lowest compared to the others. The elements Ce and La have the highest percentages at 21% and 20% respectively (FIGURE 8). As these two elements have a high potential, it is suspected that REE processing could focus on them.

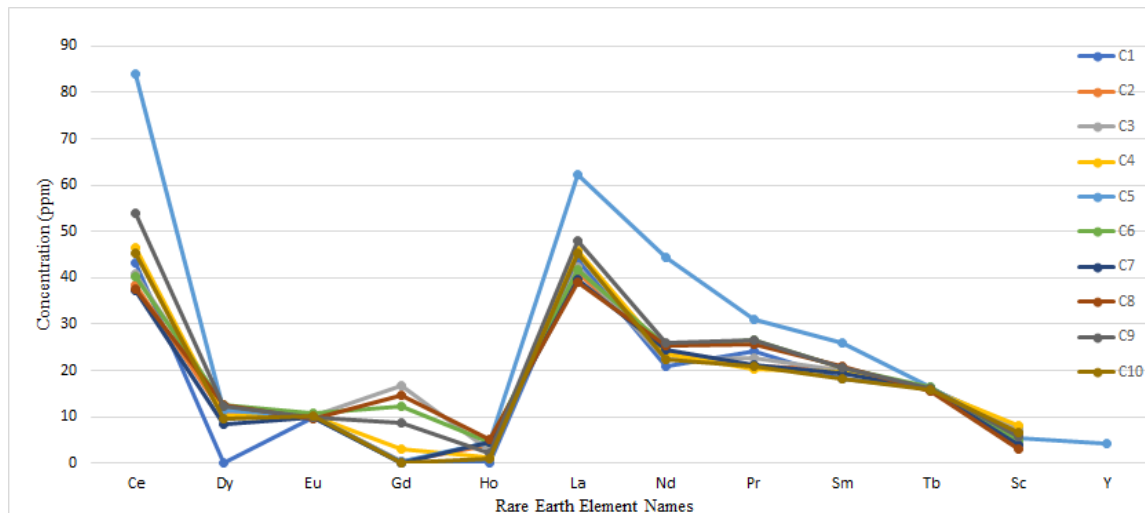


FIGURE 7. Line diagram of REEs content results using the ICP-OES test.

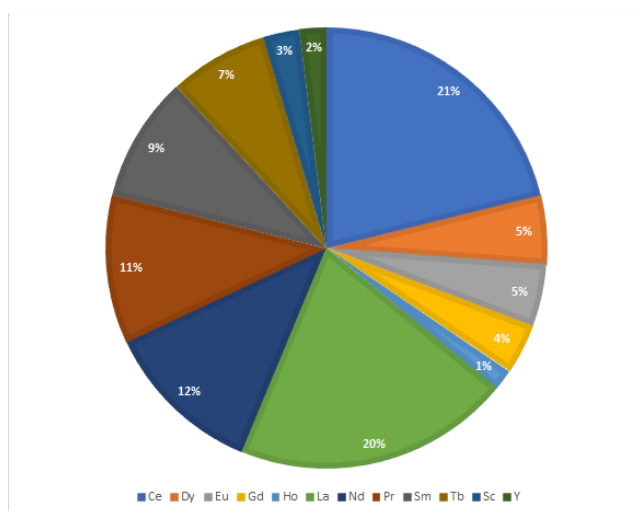


FIGURE 8. Pie chart regarding the percentage distribution of REE in the Ciuyah Mud Volcano using the ICP-OES test.

The results not only confirm the abundance of REEs in the Ciuyah Mud Volcano but also highlight the relationship between physicochemical conditions and elemental accumulation. One important factor is the subsurface fluid characteristics reflected by EC and VWC values. Variations in these parameters influence ion mobilization and enrichment processes. Zones with high EC values likely act as pathways for ion transport, enhancing REE accumulation a pattern similarly reported in other mud volcanoes such as Bledug Kuwu and Lusi [7, 9, 14, 25].

TABLE 3 shows that, in general, the REE content of the samples is higher than the REE content of the Earth's crust, meaning that the Ciuyah Mud Volcano is an area rich in REEs.

These results align with studies on Bledug Kuwu and Lusi mud volcanoes, which also reported Ce and La as dominant elements [7, 8]. However, the concentrations remain below world-class economic deposits such as Bayan Obo in Inner Mongolia, China [26]. The dominance of LREEs is consistent with the local lithology, which is dominated by alternating claystone and sandstone. Shale tends to be more abundant in LREE than in heavy rare earth elements (HREE) [3, 26, 27], and rare earth elements (REE) are generally bound to clay deposits as the main source of HREE [23].

**TABLE 3.** Comparison of samples REEs content and abundance list in the Earth's crust

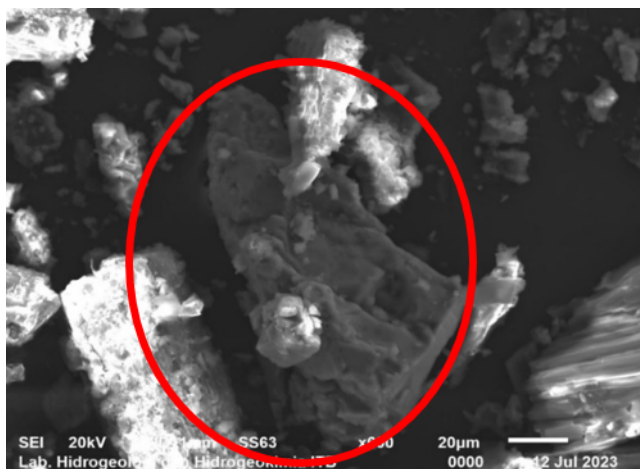
Element Name	Average Sample (ppm)	McGill (1997) (ppm)
Cerium (Ce)	46,77	20-46
Dysprosium (Dy)	11,04	4.5-7.5
Europium (Eu)	10,10	0.14-1.1
Gadolinium (Gd)	8,09	4.5-6.4
Holmium (Ho)	3,39	0.7-1.2
Lanthanum (La)	44,92	5-18
Neodymium (Nd)	25,92	12-24
Praseodymium (Pr)	23,98	3.5-5.5
Samarium (Sm)	20,41	4.5-7
Terbium (Tb)	16,08	0.7-1
Scandium (Sc)	5,86	5-10
Yttrium (Y)	4,30	28-70

The REE content in the Ciuyah Mud Volcano can be useful for various technological applications in Indonesia, such as in the fields of energy, transportation, and defence, as well as in medical equipment, electronics, ranging from batteries and semiconductors to lasers and oil-refining catalysts [28]. However, its utilization must be balanced with environmental impact assessments. Although heavy metals are naturally present due to subsurface fluid migration, even in small concentrations, they pose risks of soil and water contamination, particularly in nearby agricultural lands that are vulnerable to metal accumulation.

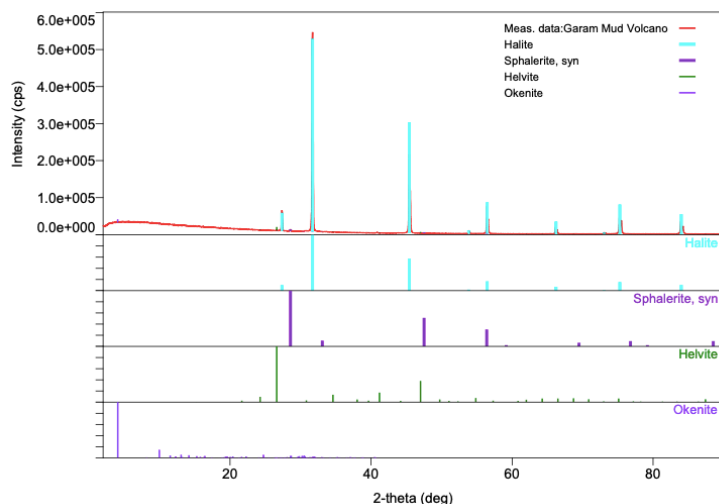
### Measurement of Salt Samples using SEM and XRD Methods

The salt sample obtained using the SEM method at the Ciuyah Mud Volcano exhibits a porous, hexagonal shape (FIGURE 9). This indicates that the salt sample from the mud volcano contains significant amounts of sodium (Na) and chlorine (Cl), which affects its surface area. Examining the graph of the percentages of the different salt elements reveals that the sample contains approximately 35.6% sodium (Na), 61.32% chlorine (Cl), and 2.06% potassium (K). Mineral identification confirmed the presence of halite (NaCl), sylvite (KCl), and helvite (FIGURE 10). The XRD data supported these findings, showing a high-intensity peak at  $2\theta \sim 35^\circ$ , confirming the dominance of halite up to 98%. The high salinity, elevated EC values, and chloride dominance suggest that Ciuyah salt is naturally formed through the interaction of hydrothermal fluids and subsurface evaporite dissolution, thus representing an authentic natural salt source. The identification of helvite in Ciuyah salt indicates the contribution of hydrothermal fluids carrying Mn, Be, and REEs within the mud volcano system. Its presence,

together with halite, enriches the mineral composition and potentially supports the exfoliating and detoxifying properties of the salt in cosmetic applications [29].



**FIGURE 9.** SEM results of Ciuyah Mud Volcano salt samples at one sampling point.



**FIGURE 10.** Graph of mineralogical elements of Ciuyah Mud Volcano salt.

The salt sample obtained using the SEM method reveals that beauty salt is porous and tetrahedral in shape (FIGURE 11). This suggests that the mud volcano salt sample contains sodium (Na) and chlorine (Cl). Examining the graph of the salt's elements and their respective percentages at 600x magnification reveals that the sample contains approximately 59.24% sodium (Na) and 25.74% sulfur (S). The presence of Na, Cl and K is observed at 100x magnification. Mineralogical compositions from SEM and XRD analyses indicated the presence of Halite (NaCl), Nahcolite (NaHCO<sub>3</sub>), Sodium Sulfide (Na<sub>2</sub>S), and Helvite, with a significant intensity peak at  $2\theta \sim 25^\circ$  reflecting the dominance of nahcolite up to 69% (FIGURE 12). These mineral constituents suggest potential applications in the cosmetic industry as "beauty salts," owing to their beneficial properties for skincare, detoxification, and exfoliation [30, 31].

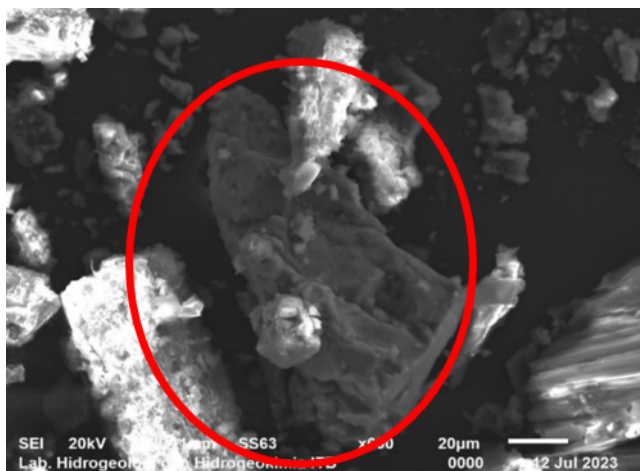


FIGURE 11. SEM results of beauty salt samples.

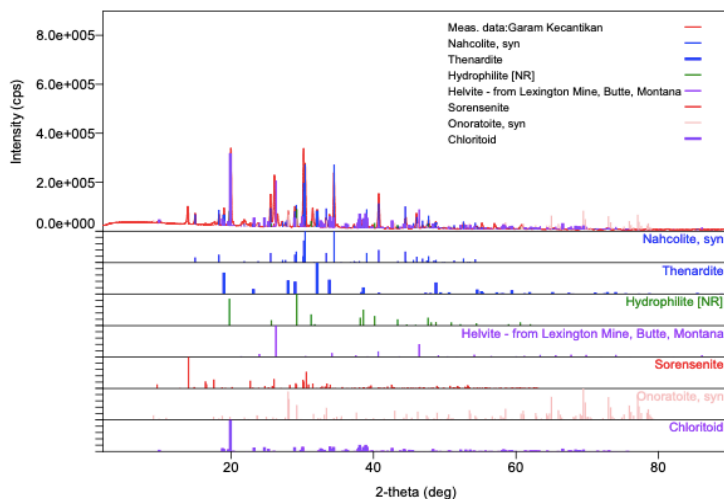


FIGURE 12. Graph of mineralogical elements of beauty salt.

## CONCLUSION

The Ciuyah Mud Volcano exhibits electrical conductivity (EC) values ranging from 253.9 to 1354 mS/cm and volumetric water content (VWC) values ranging from 126.6 to 286 m<sup>3</sup>/m<sup>3</sup>, with the highest EC value recorded at point C8. This is likely due to evaporation and ion transport processes. Measurement results for EC and TDS in the muddy water indicate high salinity, while the pH of the water is acidic to neutral. The high salinity of the water samples is possibly influenced by the northern Java Sea, which is experiencing tectonic compression. The water temperature at the volcano ranges from 30 to 41 °C, indicating hot springs. Based on XRF and ICP-OES tests, the volcano is potentially rich in rare earth elements (REEs), comprising 12 elements: Ce, Dy, Eu, Gd, Ho, La, Nd, Pr, Sm, Tb, Sc and Y, with the highest concentrations found in Ce (21%) and La (20%). Meanwhile, XRD and SEM tests reveal the presence of Halite and Helvite minerals with hexagonal morphology and large crystal grains in the salt deposits. The salt samples from the volcano have a similar composition to beauty salts, suggesting a potential application in the cosmetics industry. These findings confirm the uniqueness of the Ciuyah Mud Volcano, as one of the geological sites in West Java with the

presence of REEs and salt. Beyond advancing environmental geological knowledge, this discovery holds considerable potential to support the development of advanced materials, including permanent magnets, batteries, electronic devices, and clean energy technologies.

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